Gas hydrates: entrance to a methane age or climate threat?

2009 Environ. Res. Lett. 4 034007

(http://iopscience.iop.org/1748-9326/4/3/034007)

Environ. Res. Lett. **4** (2009) 034007 (6pp) doi:10.1088/1748-9326/4/3/034007

Gas hydrates: entrance to a methane age or climate threat?

Volker Krey[1,18], Josep G Canadell[2], Nebojsa Nakicenovic[1,3], Yuichi Abe[4], Harald Andruleit[5], David Archer[6], Arnulf Grubler[1,7], Neil T M Hamilton[8], Arthur Johnson[9], Veselin Kostov[10], Jean-Francois Lamarque[11], Nicholas Langhorne[12], Euan G Nisbet[13], Brian O'Neill[1,14], Keywan Riahi[1], Michael Riedel[15], Weihua Wang[16] and Vladimir Yakushev[17]

[1] International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, 2361 Laxenburg, Austria
[2] Global Carbon Project, CSIRO Marine and Atmospheric Research, GPO Box 3023, Canberra, ACT 2601, Australia
[3] Energy Economics Group, Vienna University of Technology, Gusshausstrasse 27-29/373-2, 1040 Vienna, Austria
[4] Social Science Consulting Unit, Japan Nus Co. Ltd, Loop-X Building 7F, 9-15 Kaigan 3-Chome, Minato-ku, Tokyo 108-0022, Japan
[5] Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Stilleweg 2, 30655 Hannover, Germany
[6] Department of the Geophysical Sciences at the University of Chicago, 5734 South Ellis Avenue, Chicago, IL 60637, USA
[7] School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA
[8] WWF International Arctic Programme, Kristian Augusts gate 7a, 0130 Oslo, Norway
[9] Hydrate Energy International, 612 Petit Berdot Drive, Kenner, LA 70065, USA
[10] Department of Physics and Astronomy, The Johns Hopkins University, 3400 N Charles Street Baltimore, MD 21218, USA
[11] Atmospheric Chemistry Division, National Center for Atmospheric Research (NCAR), PO Box 3000, Boulder, CO 80307, USA
[12] US Office of Naval Research Global, Edison House, 223 Old Marylebone Road, London, UK
[13] Department of Geology, Royal Holloway, University of London, Egham, Surrey TW20 0EX, UK
[14] Institute for the Study of Society and Environment, National Center for Atmospheric Research (NCAR), Boulder, CO, USA
[15] Earth & Planetary Sciences, McGill University, 3450 University Street, Montreal, QC, H3A 2A7, Canada
[16] Computer Network Information Center, Chinese Academy of Sciences, No. 4, 4th South Street, ZhongGuanCun, PO Box 349, Haidian District, Beijing 100080, People's Republic of China
[17] Gazprom VNIIGAZ LLC, Razvilka, Leninsky District, Moscow Region, 142717, Russia

E-mail: krey@iiasa.ac.at

Received 18 May 2009
Accepted for publication 20 August 2009
Published 7 September 2009
Online at stacks.iop.org/ERL/4/034007

[18] Author to whom any correspondence should be addressed.

Abstract

Methane hydrates, ice-like compounds in which methane is held in crystalline cages formed by water molecules, are widespread in areas of permafrost such as the Arctic and in sediments on the continental margins. They are a potentially vast fossil fuel energy source but, at the same time, could be destabilized by changing pressure–temperature conditions due to climate change, potentially leading to strong positive carbon–climate feedbacks. To enhance our understanding of both the vulnerability of and the opportunity provided by methane hydrates, it is necessary (i) to conduct basic research that improves the highly uncertain estimates of hydrate occurrences and their response to changing environmental conditions, and (ii) to integrate the agendas of energy security and climate change which can provide an opportunity for methane hydrates—in particular if combined with carbon capture and storage—to be used as a 'bridge fuel' between carbon-intensive fossil energies and zero-emission energies. Taken one step further, exploitation of dissociating methane hydrates could even mitigate against escape of methane to the atmosphere. Despite these opportunities, so far, methane hydrates have been largely absent from energy and climate discussions, including global hydrocarbon assessments and the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

Keywords: methane hydrates, methane hydrate inventory, unconventional energy resources, security of energy supply, climate change, global warming, integrated energy and climate policies

1. Introduction

Methane hydrates (or clathrates) are ice-like compounds in which methane is held in crystalline cages formed by water molecules. They are widespread in areas of permafrost such as the Arctic and in sediments on the continental margins where pressure–temperature conditions are appropriate for their formation. Methane hydrates are an energy source of potentially staggering magnitude compared with other known hydrocarbon deposits. It is thus not surprising that a number of scientific inquiries around the world are evaluating gas hydrates as a potential energy source (Nakicenovic *et al* 2000). Technologies for recovering these resources are likely to become economically feasible in the not too distant future, in which case gas resource availability would increase enormously (MacDonald 1990).

At the same time, methane hydrates might have played an important role in past climates and could have a significant effect in future human-induced climate change. Methane is a potent greenhouse gas which can be released during extraction and use of methane hydrates as an energy source. In addition, methane can reach the atmosphere through abrupt releases, e.g. due to giant submarine landslides, or chronic releases resulting from warming subsurface sediments. Models of methane dynamics in sediments predict significantly lower methane inventories if the ocean were just a few degrees warmer (Buffett and Archer 2004). Therefore there is an increasing interest in assessing the potential of methane release in a warmer world and its consequences for future climate change (Brook *et al* 2008, Schiermeier 2008, Westbrook *et al* 2009).

2. Methane hydrate occurrences

Despite the fact that methane hydrates are potentially an enormous energy source and a factor in global warming, the magnitude of global methane hydrate occurrences and, in particular, their geographical distribution and depth profile are very uncertain (see figure 1 for known hydrate accumulations and global distribution of appropriate conditions for methane hydrate formation). At a recent workshop that brought together experts on both the energy and climate dimensions of methane hydrates (Bohannon 2008), an attempt was made to assign likelihoods[19] to occurrence estimates: with high confidence a size exceeding 1000 GtC (1 Gt = 1 billion tons) was considered to be very likely. With medium confidence the global methane hydrate inventory is likely to be in the range of 1000–10 000 GtC (equivalent to ∼2000–20 000 trillion cubic meters, or ∼70–700 zettajoules of natural gas). For comparison, the global inventory of fossil fuels including coal is estimated to be around 5000 GtC (Rogner 1997), i.e. in the same order of magnitude as the hydrates inventory alone.

Even more uncertain are the fraction of hydrates that might become available as an energy resource and the fraction which could become vulnerable to anthropogenic climate change. This uncertainty partly results from the limitations of currently available seismic and electromagnetic techniques to reliably characterize and quantify hydrate accumulations (Boswell 2007, Johnson and Smith 2006). Thus, further development of advanced seismic techniques, extended drilling programs, but also improved inventory modeling are needed to reduce uncertainty.

3. Energy potential

Today's energy system is dependent on hydrocarbons, especially oil, but increasingly also natural gas. Eighty per cent of the current global energy supply is of fossil origin. However, decarbonization of energy supplies is a historical evolutionary

[19] We adopt here the convention of the IPCC AR4 for the treatment of uncertainty (see IPCC (2005)).

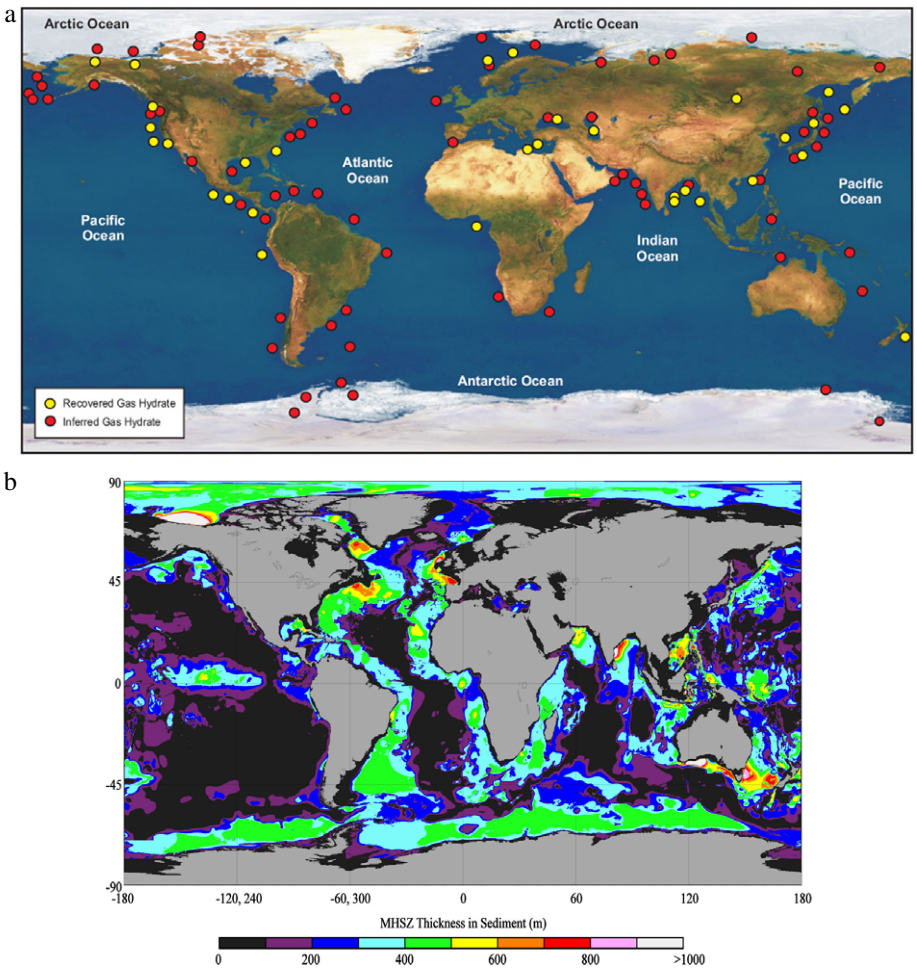

Figure 1. (a) Distribution of known methane hydrate accumulations (courtesy of Council of Canadian Academies (2008), based on data from Kvenvolden and Rogers (2005)). (b) Estimated global methane hydrate stability zone thickness in seafloor sediments (courtesy of Warren Wood, Naval Research Laboratory). The methane hydrate stability zone indicates where appropriate temperature and pressure conditions for the formation of hydrates can be found (see also inlay of figure 2).

process. Traditional fuels such as biomass with high carbon intensity were substituted by coal which later on was replaced by oil further reducing the carbon intensity of primary energy. Both transitions took about 50 years (Grubler and Nakicenovic 1996). Given these dynamics grounded on the inherent inertia of technological change, it is not very likely that we will be able to shift to non-carbon primary energy sources by the middle of the century, although doing so would be desirable from a climate perspective. Global emissions would have to peak within the next two decades and fall toward zero in the second half of the century if we want to limit global mean temperature rise to about two degrees Celsius by the end of the century (IPCC 2007a).

This opens a large gap between energy demand and the required emission reductions to avoid dangerous human interference with the climate system. At the same time it provides an opportunity for methane hydrates to become an important source of energy as a bridge between carbon-intensive fossil energies and zero-emission energies, given methane is the least carbon-intensive of all hydrocarbons. Even a small recoverable fraction of the large gas-in-place estimates might still be sufficient to enter a 'methane age' (Nakicenovic 2002). As little as one thousands part of the global methane hydrates inventory would suffice to cover current annual global energy needs. Such a transition can occur through technological change, better geological knowledge and changing economics—greatly supported by sustained high oil prices at US$50/barrel or more.

On the one hand, characteristics of hydrate deposits vary significantly and along with these characteristics the challenges for technological development. Natural gas hydrates from onshore sub-permafrost which can be exploited by use of semi-conventional technology are the low hanging fruit. In fact, some fraction of the gas extracted from the Messoyakha gas field in Western Siberia may have originated from hydrates, although quantities and evidence are disputable (Collett and Ginsburg 1998, Ginsburg *et al* 2000). Leveraging existing infrastructure such as that in Western Siberia and the North Slope of Alaska enhances the economics of hydrate exploitation substantially. Extensions of current technologies can also be used to exploit ocean hydrates, but extended exploitation will require a paradigm shift in production technologies (e.g. autonomous integrated exploration and production units) as the bulk of hydrates is

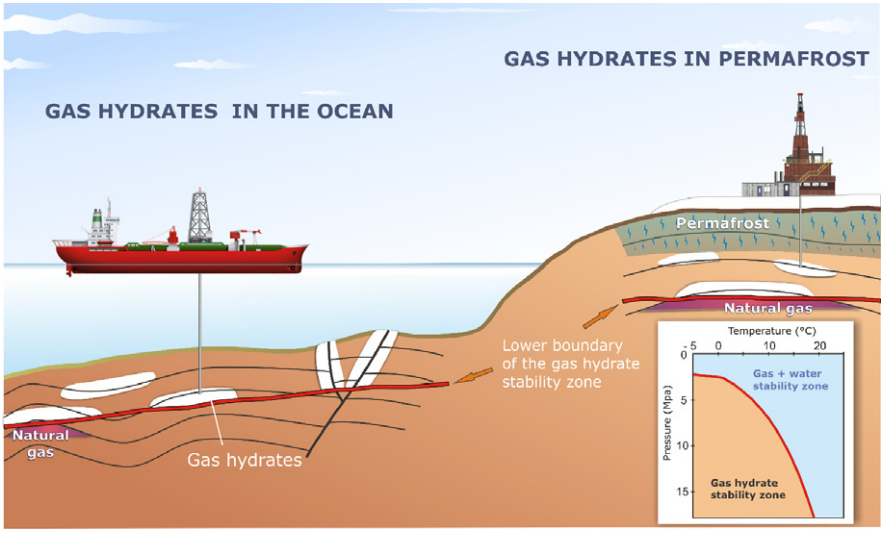

Figure 2. Illustration of methane hydrates recovery onshore from below the permafrost in the Arctic and offshore from the sediments of the continental margins (courtesy of Bundesanstalt für Geowissenschaften und Rohstoffe). The inlay in the lower right corner shows appropriate temperature and pressure conditions for the formation of methane hydrates.

located in deposits with low hydrate concentrations (Boswell and Collett 2006). Figure 2 illustrates the recovery process of gas hydrates from the Arctic permafrost as well as offshore from the continental margins. Such developments would require dedicated research and development efforts beyond the activities of current exploration industry. For ease of exploitation the order could be (i) sub-permafrost hydrates, (ii) offshore accumulations close to consumers, and (iii) remote offshore accumulations.

On the other hand, gas hydrate exploitation development is driven by national policies and scarcity of alternative energy resources, i.e. security of supply concerns. Therefore, the largest efforts to develop technology are currently made by countries with limited domestic resources and/or growing energy demand in the future. Accordingly Japan, South Korea, India, China and the United States are the countries with the largest hydrate research and development programs (Collett *et al* 2008). As a result, it is likely that some commercial production will commence by 2020 and expand to other locations over the following decade.

Methane hydrates could make methane the energy source of choice in the medium-term and a bridge towards carbon-free energy sources. However, if the largest potential is to be realized, carbon capture and storage is required under any CO_2 stabilization. For example, as the methane is extracted and burned in situ, CO_2 hydrate could be deposited simultaneously. Given that energy resources from methane hydrate could be of the same order of magnitude as those of coal, any significant extraction would contribute to anthropogenic climate change without carbon capture.

4. Climatic dimension

Because of its lower concentration in the atmosphere than CO_2, the infrared absorption bands of methane are less saturated and therefore methane is a more powerful greenhouse gas (IPCC 2007b). Methane hydrate seems intrinsically vulnerable on Earth; nowhere at the Earth's surface is it stable to melting and release of the methane, and it floats in water, so the only factor holding it at high pressure is the weight of the mud overlying it in coastal margin sediments. A few degrees of warming in the deep ocean can have a significant impact on the stability of the hydrate, and it is known that the temperature of the deep ocean responds to changes in surface climate, albeit with a lag of centuries to millennia. Hence, there are concerns that climate change could trigger significant methane releases from hydrates and thus could lead to strong positive carbon–climate feedbacks (Schiermeier 2008).

Holes in the ocean's sediment surface (pockmarks) and submarine landslides are among the mechanisms of eruptive methane release as a result of hydrate destabilization. Quantities released in single events are constrained to about 1–5 GtC, resulting in increased radiative forcing of up to 0.2 W m^{-2} if all the methane were to reach the atmosphere (Archer 2007). For comparison, the best estimate total change in radiative forcing from pre-industrial times until today is 1.6 W m^{-2} (IPCC 2007b). Methane releases from hydrates that could be most significant to climate change are more likely to be of chronic nature. Changes in the ocean bottom temperature can have a substantial impact on the hydrate stability zone and thus on the equilibrium methane hydrate inventory (Buffett and Archer 2004, Dickens 2001). However, due to the long ventilation times of the deep ocean (∼100–1000 years), where the bulk of methane hydrates resides, and the slow propagation of the temperature signal into the sediment column (∼180 m/1000 years), a new equilibrium is only reached on a timescale of 1000–10 000 years. Moreover, the fraction of methane from the bottom of the ocean that reaches the atmosphere is uncertain and dependent on the transport mechanism (e.g. bubbles, dissolved) (Lamarque 2008). Methane's oxidation lifetime dissolved in seawater is about 50 years (Rehder *et al* 1999) and thus it would largely reach the atmosphere as CO_2.

An important exception from these long response times is Arctic hydrates because the stability zone sometimes reaches to just 200 m below the surface and, in some cases, methane hydrates can be found at only some tens of meters in a metastable state caused by the permafrost environment (Yakushev and Chuvilin 2000). Methane hydrate accumulations on the shallow Arctic shelf and hydrates disseminated in permafrost are poorly quantified and thus better inventories are essential to estimate methane release from these sources as a result of global warming. Moreover, rapid warming well above the global average makes the Arctic hydrates particularly vulnerable to climate change (Westbrook *et al* 2009). This in turn is likely to become a safety issue in conventional oil and gas production given the growing interest to start production in newly opened areas in the Arctic resulting from the rapid melting of sea ice. However, if carefully done, exploitation of dissociating methane hydrates could even mitigate against escape of methane to the atmosphere. This situation is unique for gas hydrates and distinguishes them from other conventional and unconventional natural gas occurrences.

5. Recommendations

To enhance our understanding of both vulnerability and opportunity of methane hydrates, it is necessary to improve existing estimates of hydrate occurrences, their geographical distribution and depth profile. Such an assessment would greatly benefit from coordinated international research and, in particular, collaborative effort at selected oceanic and Arctic sites. In addition, dynamics of the hydrates inventory under changing environmental conditions, mainly pressure and temperature, need to be better understood, particularly the sensitivity of deep ocean temperature to surface climate change and temperature transfer into the deposits. All this requires advances in seismic techniques, extended drilling, but also improvements in reservoir modeling. An expanded observational system to monitor methane in the oceans and atmosphere, including its isotopic composition for enhanced capacity to detect emission sources, is needed.

Methane hydrates may offer a great opportunity as an energy source but at the same time can become an important driver of climate change from the burning of methane for energy production and from destabilization due to global warming. A key development to avoid unintended climate effects will be to integrate the agendas (and policies) of energy security and climate change. Therefore, development of carbon capture and storage should accompany that of hydrate extraction technologies to clear the way for methane hydrates to become a 'bridge fuel' towards a low carbon future. Taking the integration of energy and climate change agenda one step further, 'preventive exploitation' of dissociating methane hydrates could even mitigate against escape of methane to the atmosphere while providing a high quality fuel at the same time. Hydrate technologies should therefore not be ignored and might be easier to develop and deploy than other alternatives as they can build on existing infrastructure and partly developed and deployed technologies.

In any case, an integrative approach that addresses both energy and climate dimensions of methane hydrates is needed to avoid negative side effects of their deployment. Moreover, dealing with methane hydrates in a disciplinary context only is a lost opportunity as there are large co-benefits in studying these dimensions jointly.

Acknowledgments

This article is the outcome of the workshop 'Vulnerability and Opportunity of Methane Hydrates', co-organized and sponsored by Global Carbon Project and the International Institute for Applied Systems Analysis.

References

Archer D 2007 Methane hydrate stability and anthropogenic climate change *Biogeosciences* **4** 521–44

Bohannon J 2008 ENERGY: weighing the climate risks of an untapped fossil fuel *Science* **319** 1753

Boswell R 2007 Resource potential of methane hydrate coming into focus *J. Petroleum Sci. Eng.* **56** 9–13

Boswell R and Collett T 2006 The gas hydrates resource pyramid *Fire in the Ice—Methane Hydrate Newsletter* US Department of Energy (DoE)—National Energy Technology Laboratory (NETL)

Brook E, Archer D, Dlugokencky E, Frolking S and Lawrence D 2008 *US Climate Change Science Program—Synthesis and Assessment Report 3.4: Abrupt Climate Change,* ed US Geological Survey

Buffett B and Archer D 2004 Global inventory of methane clathrate: sensitivity to changes in the deep ocean *Earth Planetary Sci. Lett.* **227** 185–99

Collett T S and Ginsburg G D 1998 Gas hydrates in the Messoyakha gas field of the West Siberian Basin—A re-examination of the geologic evidence *Int. J. Offshore Polar Eng.* **8** 22–9

Collett T S, Johnson A, Knapp C and Boswell R 2008 Natural gas hydrates—a review *Natural Gas Hydrates—Energy Resource Potential and Associated Geologic Hazards* ed T S Collett *et al* (Tulsa, OK: American Association of Petroleum Geologists)

Council of Canadian Academies 2008 *Energy From Gas Hydrates: Assessing the Opportunities and Challenges for Canada*

Dickens G R 2001 On the fate of past gas: what happens to methane released from a bacterially mediated gas hydrate capacitor? *Geochem. Geophys. Geosyst.* **2** 1037

Ginsburg G D, Novozhilov A A, Duchkov A D, Prasolov E M, Zavarzin I V and Collett T S 2000 Do natural gas hydrates exist in cenomanian strata of the Messoyakha gas field? *Geol. Geofiz.* **41** 1165–77

Grubler A and Nakicenovic N 1996 Decarbonizing the global energy system *Technol. Forecasting Social Change* **53** 97–110

IPCC 2005 *Guidance notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties* (Geneva: Intergovernmental Panel on Climate Change (IPCC))

IPCC 2007a *Climate Change 2007: Mitigation of Climate Change* Intergovernmental Panel on Climate Change

IPCC 2007b *Climate Change 2007: The Physical Science Basis* Intergovernmental Panel on Climate Change

Johnson A H and Smith M A 2006 Gas hydrate E&P: dispelling the myths *Hart's E and P* (September)

Kvenvolden K A and Rogers B W 2005 Gaia's breath–global methane exhalations *Marine Petroleum Geol.* **22** 579–90

Lamarque J-F 2008 Estimating the potential for methane clathrate instability in the 1%-CO_2 IPCC AR-4 simulations *Geophys. Res. Lett.* **35** L19806

MacDonald G J 1990 The future of methane as an energy resource *Annu. Rev. Energy* **15** 53–83

Nakicenovic N 2002 Methane as an energy source for the 21st century *Int. J. Global Energy Issues* **18** 6–22

Nakicenovic N, Gritsevskii A, Grübler A and Riahi K 2000 *Global Natural Gas Perspectives* (International Gas Union (IGU), Office of the Secretary General and IIASA) p 83

Rehder G, Keir R S, Suess E and Rhein M 1999 Methane in the northern Atlantic controlled by microbial oxidation and atmospheric history *Geophys. Res. Lett.* **26** 587–90

Rogner H H 1997 An assessment of world hydrocarbon resources *Annu. Rev. Energy Environ.* **22** 217–62

Schiermeier Q 2008 Fears surface over methane leaks *Nature* **455** 572–3

Westbrook G K *et al* 2009 Escape of methane gas from the seabed along the West Spitsbergen continental margin *Geophys. Res. Lett.* **36** L15608

Yakushev V S and Chuvilin E M 2000 Natural gas and gas hydrate accumulations within permafrost in Russia *Cold Regions Sci. Technol.* **31** 189–97